Ductile Regime Machining of Silicon Nitride: Experimental and Numerical Analyses

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Abstract

Recent advances in precision machining technology have shown that ductile regime machining of advanced ceramics such as silicon nitride is possible under controlled cutting conditions. In this paper, select results from experimental and numerical work being carried out on the ductile-regime machining of silicon nitride are discussed. Machining tests are carried out for depths of cut ranging from 250nm to 10µm. Force and surface roughness data collected from diamond turning of silicon nitride samples are presented. In a previous study, the authors reported results from numerical simulations of orthogonal machining of silicon nitride using a pressure-independent material model with von Mises yield criterion. In the present work, the mechanical behavior of silicon nitride is treated using the Drucker-Prager yield criterion implemented in the commercial machining software ***AdvantEdge***. Numerical simulations are executed for depths of cut ranging from 1 µm to 40 µm and at rake angles from 0° to -60°.

1 INTRODUCTION

Recent research on precision machining of brittle materials has indicated that, under certain controlled conditions, ductile regime material removal of ceramics is possible at low depths of cut and high pressures [1]. An advantage of ductile machining over brittle machining is the minimal subsurface damage with a surface roughness of the order of a few nanometers. Nano-indentation experiments suggest that the ductile behavior of many ceramic and semiconductor materials is pressure-induced with the brittle-to-ductile transition taking place when the hydrostatic pressure during loading approaches the hardness values of these materials [2]. In the present work, focus is on the pressure-induced phase transformation of ceramics (specifically, silicon nitride) during machining. At low depths of cut and low cutting speeds, the high pressure field in the workpiece ahead of the cutting tool causes the material to undergo phase transformation to a metallic phase giving rise to ductile behavior during machining. In particular, brittle to ductile phase transformation has been reported during the single-point diamond turning of silicon nitride samples [3]. When depths of cut and cutting speeds are high, the temperatures within the workpiece are large enough that thermal softening is the dominant mechanism for phase transformation.

In this paper, a few results from the experimental and computational studies of ductile machining of silicon nitride being carried out at UNC-Charlotte are presented. Silicon Nitride samples are machined on a diamond turning machine with depths of cut ranging from 250nm to 20µm. Force data was collected and surface roughness characteristics were analyzed for ductile-regime machining. Chip morphology is also studied for the machining process using Scanning Electron Microscopy (SEM). The studies indicate that ductile mode machining is possible at micron and submicron level depths of cut.

Numerical simulations have also been conducted to study the ductile regime machining of silicon nitride using the commercial machining software, ADVANTEDGE [4]. In a previous paper [5], a rate-dependent, power-law constitutive model with a von Mises yield criterion was used. However, as mentioned above, the phase transformation in silicon nitride at low depths of cut and low cutting speeds is pressure-induced and hence the material model must include pressure sensitivity. In order to account for the pressure sensitivity of silicon nitride, the pressure-sensitive, Drucker-Prager yield criterion has been implemented in ADVANTEDGE. Results from numerical simulations incorporating the modified yield criterion are reported with the emphasis on the effect of depth of cut and rake angles on the pressure field (and hence on the conditions suitable for ductile machining) in the silicon nitride workpieces.

2 EXPERIMENTS

Recent work on single point diamond turning of semiconductors such as Silicon and Germanium showed that these materials can be machined in a ductile fashion with a minimal subsurface damage. As part of an ongoing study to extend this research to other brittle materials, machining experiments were carried out on silicon nitride to study the conditions under which silicon nitride can be machined in ductile regime. In the following, results from a recent set of such experiments carried out on silicon nitride samples (grade GS-44) are presented. The samples were ground prior to machining ($R_a \approx 600$ nm).A batch of 140 samples are machined at depths of cut 250 nm, 500 nm, 1 µm, 5 µm and 10 µm (35 samples for each depth) using polycrystalline diamond tools.

2.1 Machining forces and surface roughness analyses

Machining force data is measured using KISTLER dynamometer and analysis is made with MATLAB software. From the machining tests it is observed that thrust force dominates over cutting force for all the depths of cut. Machining forces as a function of depth of cut is plotted in figure 1. An increase in the thrust force for 250nm depth of can be attributed to chipping of the tool. Cutting edge radius of the diamond tool is increased due to chipping and this caused higher thrust force and also higher surface roughness.

Surface roughness is measured using Wyko white light interferometer. Average and RMS values of surface roughness are plotted against depth of cut in figure 2. For depth of cut less than 1µm, the values of roughness are comparable with ground specimens. The machining parameters are listed in table1.

Spindle speed	100rpm
Cross-feed	5µm/rev
Rake angle	-5°
Tool	Polycrystalline Diamond
Cutting edge radius	10µm

Table1 Machining parameters.

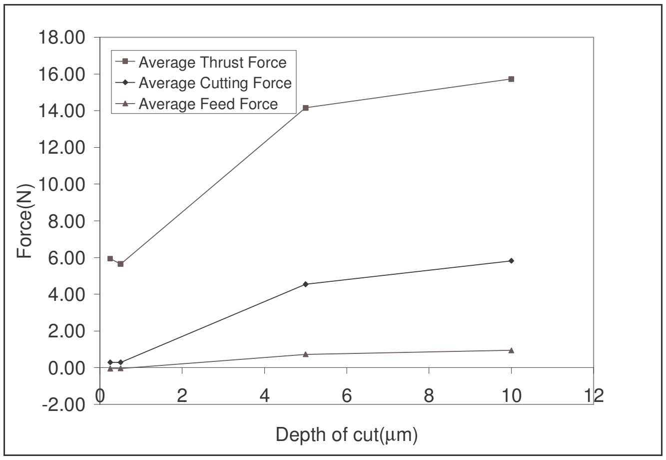


Figure 1: Variation of machining forces with depth of cut.

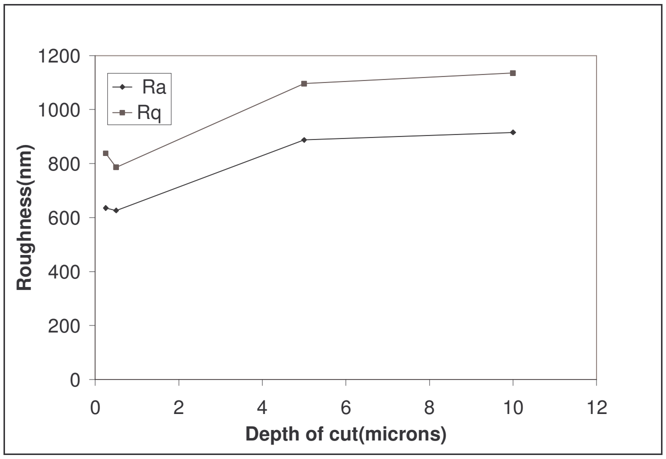


Figure 2: Variation of average and r.m.s roughness with depth of cut.

2.2 Chip Morphology

Chip morphology is studied for the machined depths using Scanning Electron Microscopy. It is observed that there is possibility of obtaining plastically deformed chips in the machining process for depths of cut 1μm and 500nm. Images of chips for depths 500 nm and 1 μm are shown in Figures 3 and 4. Thinning and curling of chips is an indication of ductile chip formation.

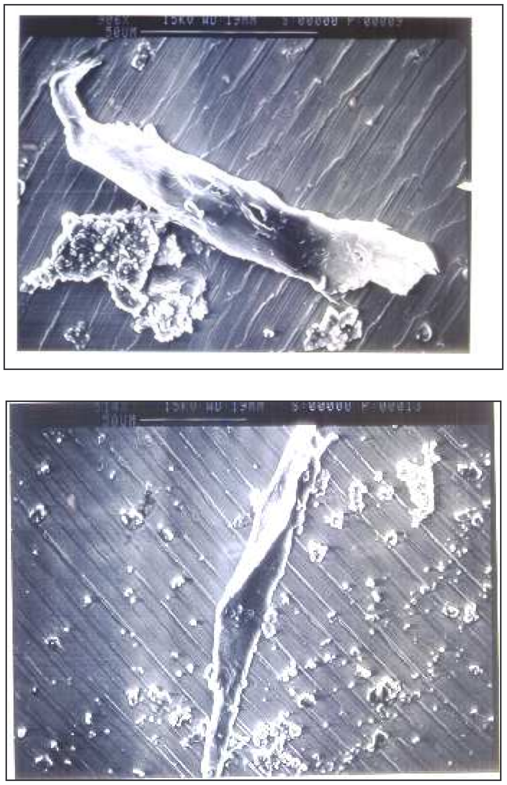


Figure 3: SEM images of chips for depth of cut =1μm

Figure 4: SEM images of chips for depth of cut =500nm

3 DRUCKER-PRAGER MATERIAL MODEL (YIELD CRITERION)

The mechanisms governing the ductile behavior of ceramic and semiconductor materials are not completely understood. Possible mechanisms for plastic deformation of silicon have been hypothesized in [2]. A constitutive model taking into account the pressure-induced phase transformation has been recently proposed in [6]. In this work, the pressure-sensitive ductile behavior of silicon nitride is modeled by using Drucker-Prager yield condition [7] according to which, yielding occurs when the equality

$$\sqrt{3J_2} + I_1\alpha - \kappa = 0 \qquad (1)$$

is met. In the above, I_1 is the first invariant of stress tensor, J_2 is the second invariant of the deviatoric stress tensor S_{ij}, κ is the material constant and α is the pressure sensitivity coefficient. The quantity J_2 is given by

$$J_2 = \frac{1}{2} S_{ij} S_{ij} \qquad (2)$$

or in terms of the principal stresses, it is given by

$$J_2 = \frac{1}{6}\left[(\sigma_1 - \sigma_2)^2 + (\sigma_2 - \sigma_3)^2 + (\sigma_3 - \sigma_1)^2\right] \qquad (3)$$

In the above σ_i are principal stresses. The constant κ is determined from the yield stresses in uniaxial tension and compression. Thus, let σ_t and σ_c be the yield stress in tension and compression respectively. Then noting that for uniaxial stress state, $J_2 = \frac{\sigma_1^2}{3}$ one can find the constant κ from the yield criterion as

$$\kappa = \frac{2\sigma_t\sigma_c}{\sigma_t + \sigma_c} \tag{4}$$

Experimental evidence indicates that silicon nitride behaves in a ductile fashion when the maximum hydrostatic pressure in the workpiece during machining is of the same order of magnitude as the hardness [2]. In order to obtain this in simulations, the compressive yield stress is set equal to the hardness of workpiece (*H*) and tensile yield is set to $H/2.2$, κ and α are obtained from the yield criterion. These values are used in the numerical simulations.

4 NUMERICAL SIMULATIONS

The primary objective of numerical simulations is to study the effect of varying various process parameters on the pressure field within the workpiece. The orthogonal machining model used in the ADVANTEDGE software is shown in figure 5. The simulations have been carried out for GS44 Silicon Nitride workpiece material. For this material, the Young's modulus is 311 GPa, Poisson ratio is 0.27, density is 3210 Kg/m^3 and hardness is 15.2 GPa at room temperature.

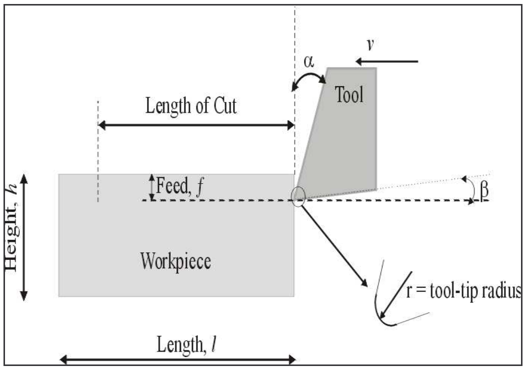


Figure 5: AdvantEdge machining model (α - rake angle, β - clearance angle, v - cutting velocity).

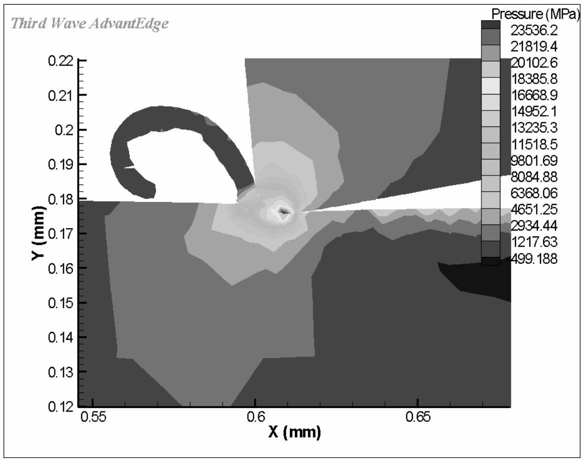
4.1 Effect of depth of cut

Depths of cut of 1 µm, 5 µm, 10 µm, 25 µm and 40µm were considered in the numerical simulations for a cutting speed of 25 m/min and -5° rake angle. The pressure sensitivity coefficient was taken to be α = 0.38 and κ = 9.4 GPa. The modeling parameters are shown in table 2. Since the cutting speeds considered in the following simulations are small, the material behavior is taken to be insensitive to thermal conditions. In ADVANTEDGE software, this is achieved by turning off the thermal softening effects. In the following, results from varying the depth of cut are presented.

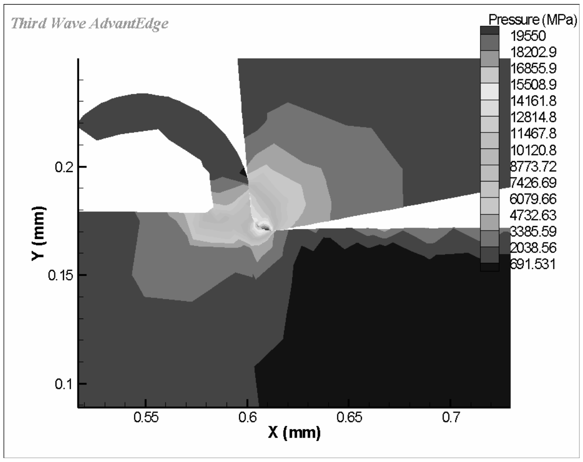
Pressure Sensitivity Coefficient	0.38
Speed	100 rpm
Rake angle	-5°
Hardness (H)	15.2 GPa
Cutting edge radius	10 µm

Table 2 Modeling parameters.

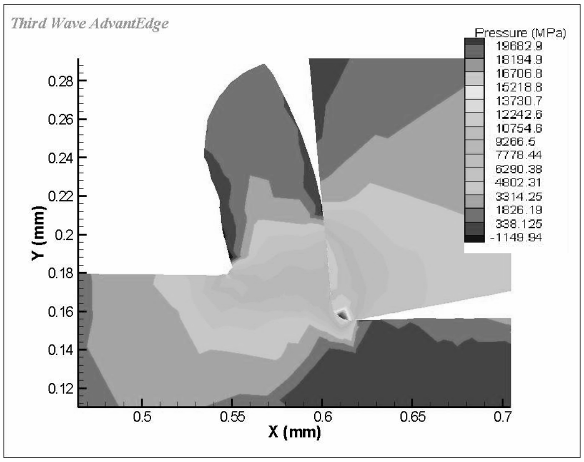
For depth of cut of 5 µm (based upon the simulation results) it is observed that the hydrostatic pressure in the workpiece (just ahead of the cutting tool) approaches values comparable to the hardness of the workpiece. The pressure distribution for different depths is shown in figure 6.



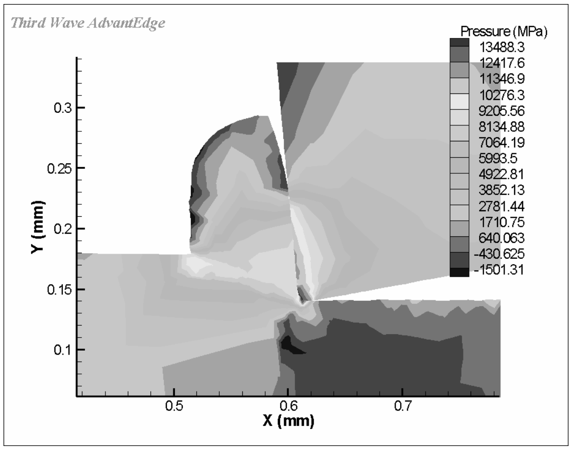
(a) 5µm



(b) 10µm



(c) 25µm



(d) 40µm

Figure 6: Pressure distribution in the workpiece for various depths of cut.

The variation of cutting and thrust forces with the depth of cut is shown in figure 7. The thrust force is higher than cutting force at 5µm depth of cut. This may be due to the fact that the cutting edge radius of the tool is larger than the depth of cut.

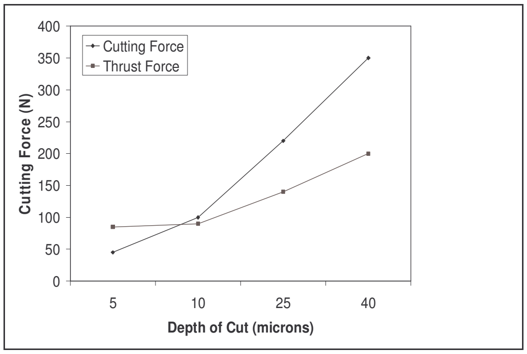


Figure 7: Variation of cutting and thrust forces with depth of cut.

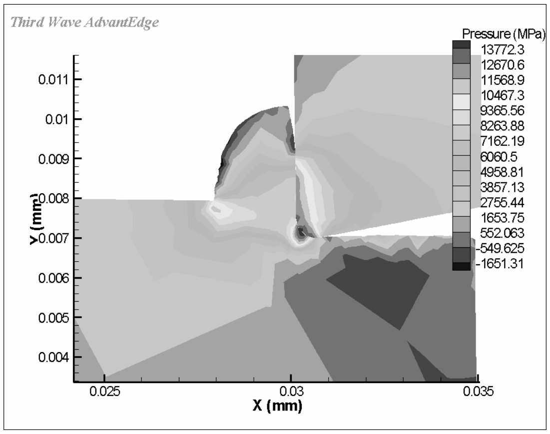
4.2 Effect of rake angle

From the studies carried on single point diamond turning of ceramics, it is observed that negative rake angle induces high compressive stress state ahead of the cutting tool [8]. Work material passing through this high-pressure zone undergoes brittle to ductile transition. To study this effect of negative rake angle on pressure distribution, simulations were conducted for rake angles varying from 0° to -60° at 10 µm, 5 µm and 1 µm depths of cut. It can be noted that results from simulations for 1 µm depth of cut only are presented here.

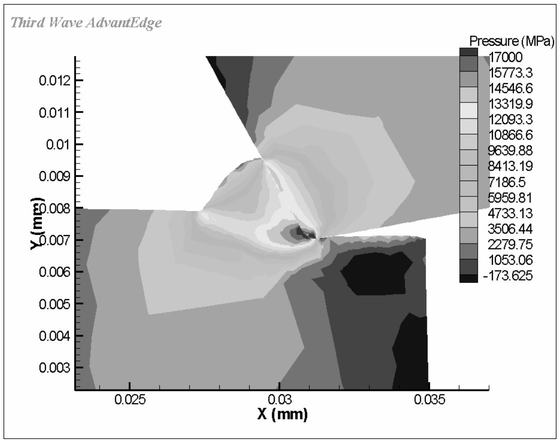
Pressure distribution for different rake angles is plotted in figure 8. It is implied from these results that for negative rake angles and at 1 µm depth of cut, ductile behavior of silicon nitride is favored when pressure in the deformation zone approaches hardness values. For -60° rake angle, pressures greater than hardness were observed ahead of the tool-tip. The modeling parameters are listed in table 2.

Pressure Sensitivity Coefficient	0.38
Speed	1000 rpm
Hardness (H)	15.2 GPa
Depth of Cut	1 µm
Tool tip radius	0.5 µm.

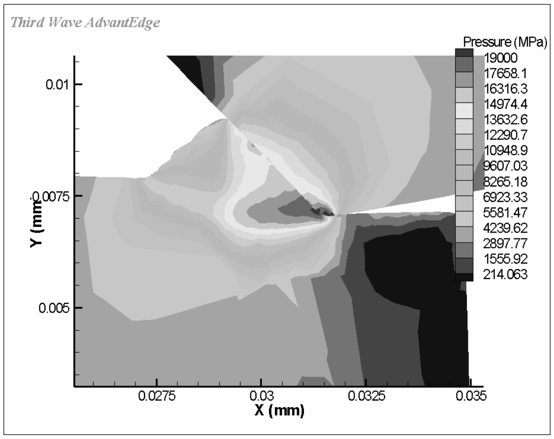
Table 2 Modeling parameters



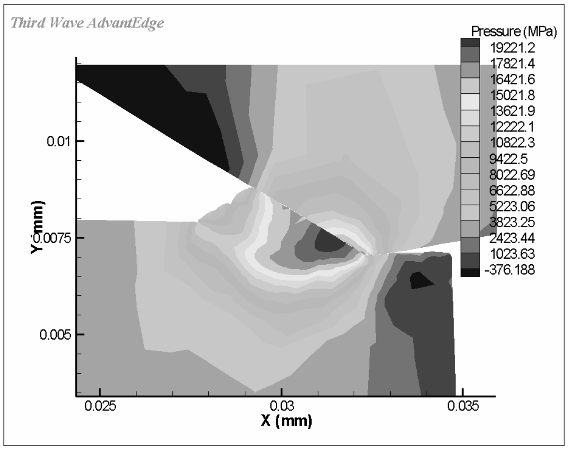
(a) 0°



(b) -30°



(c) -45°



(d) -60°

Figure 8: Pressure distribution in the workpiece for various rake angles.

The variation of machining forces with rake angle is plotted in figure 9. As the rake angle decreases, thrust force dominates over the cutting force indicating that high pressures are developed in the workpiece for higher negative rake angles.

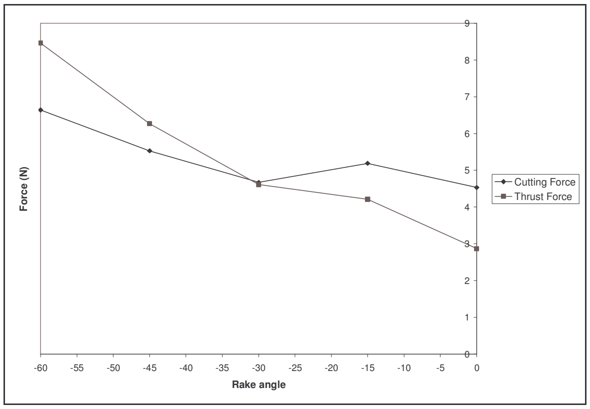


Figure 9: Variation of cutting and thrust forces with rake angle.

The maximum temperatures in these simulations are very much below the melting point of the workpiece suggesting that ductile behavior is less dependent on temperature than pressure.

5 CONCLUSIONS

The numerical results indicate that Drucker-Prager yield criterion coupled with a rate independent material model is a reasonable first-step in modeling ductile machining of silicon nitride. The parametric study shows that when the depths of cut are small, the pressure in the workpiece approaches the hardness value of Silicon Nitride in the region near the workpiece-tool interface indicating that the material transitions to ductile mode. High pressures are developed in the primary deformation zone for negative rake angles for 1 μm depth of cut. Experiments show that material removal can be ductile when machining is carried out at depths less than 1μm. Scanning Electron Microscopy technique is used to image chips obtained from machining. These images show the possibility of ductile machining mode for lower depths of cut. Currently, work is in progress to develop more realistic models to incorporate the pressure-induced phase transformation into the constitutive behavior.

6 ACKNOWLEDGEMENTS

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